Beam Cleaning in **High-Power Proton Accelerators**

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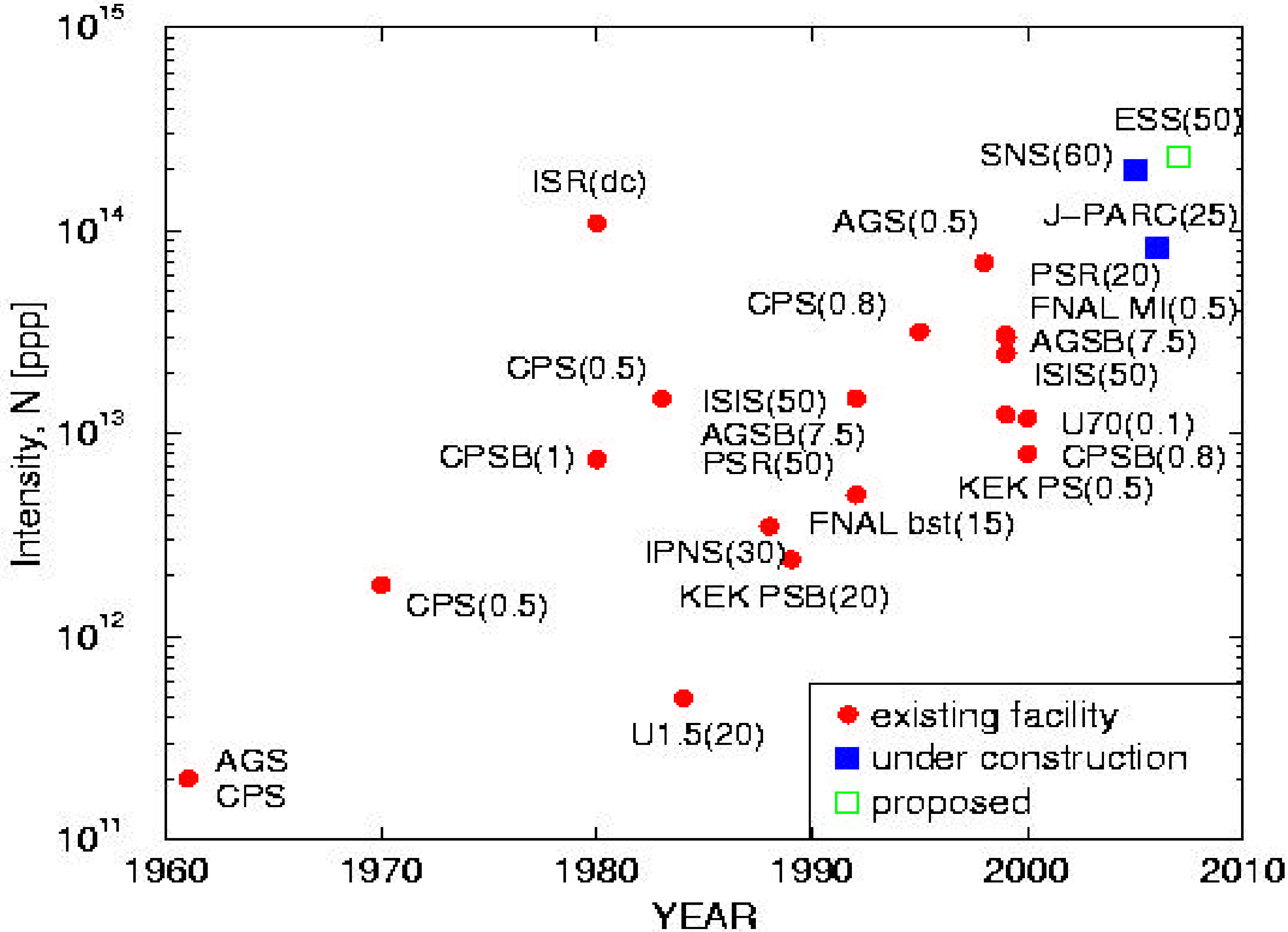
May 23 - 26, 2003

HALO'03 Workshop

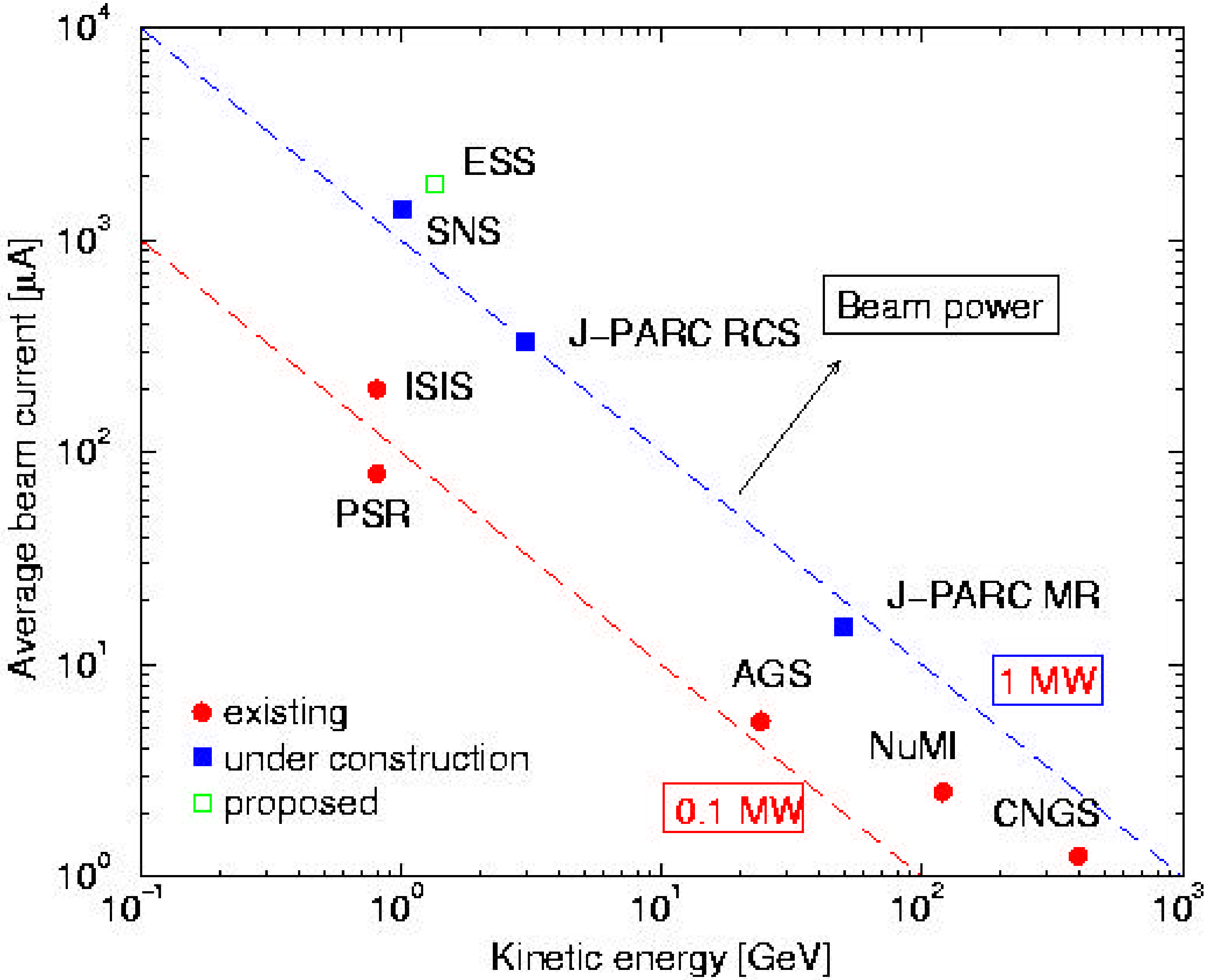
Outline

- Introduction
  - Motivation; Collimation in existing and planned machines
- Guiding Principles
  - Low-energy cleaning; Fault protection
  - Impedance & secondary yield consideration
- Beam Cleaning
  - H^- beam halo cleaning
  - Proton beam halo cleaning
  - Electron cleaning
- Collimator Design & Handling
  - Primary scraper & secondary collector
  - Remote handling & quick access
- Summary

Evolution of high-intensity rings



Advance in beam power

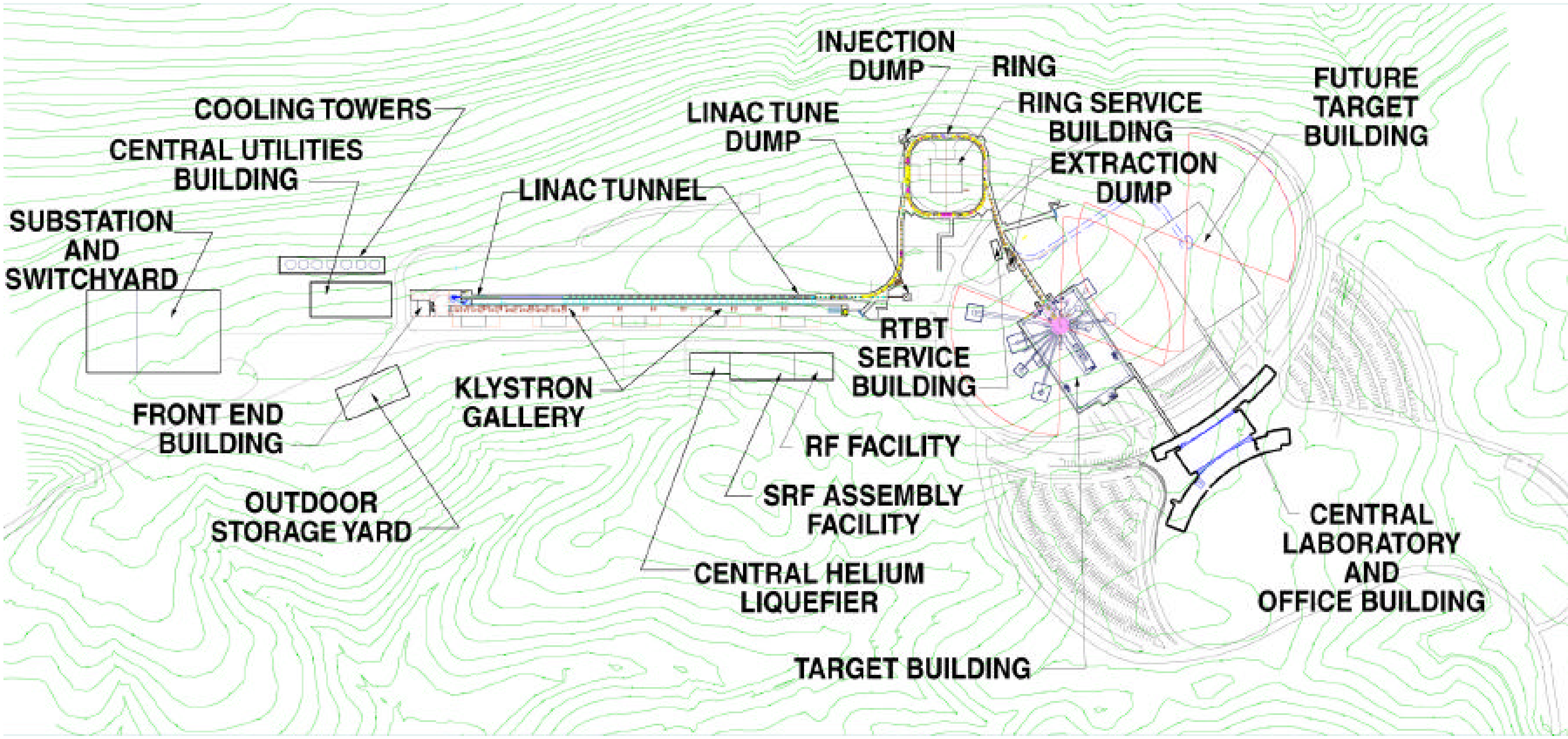


Motivation

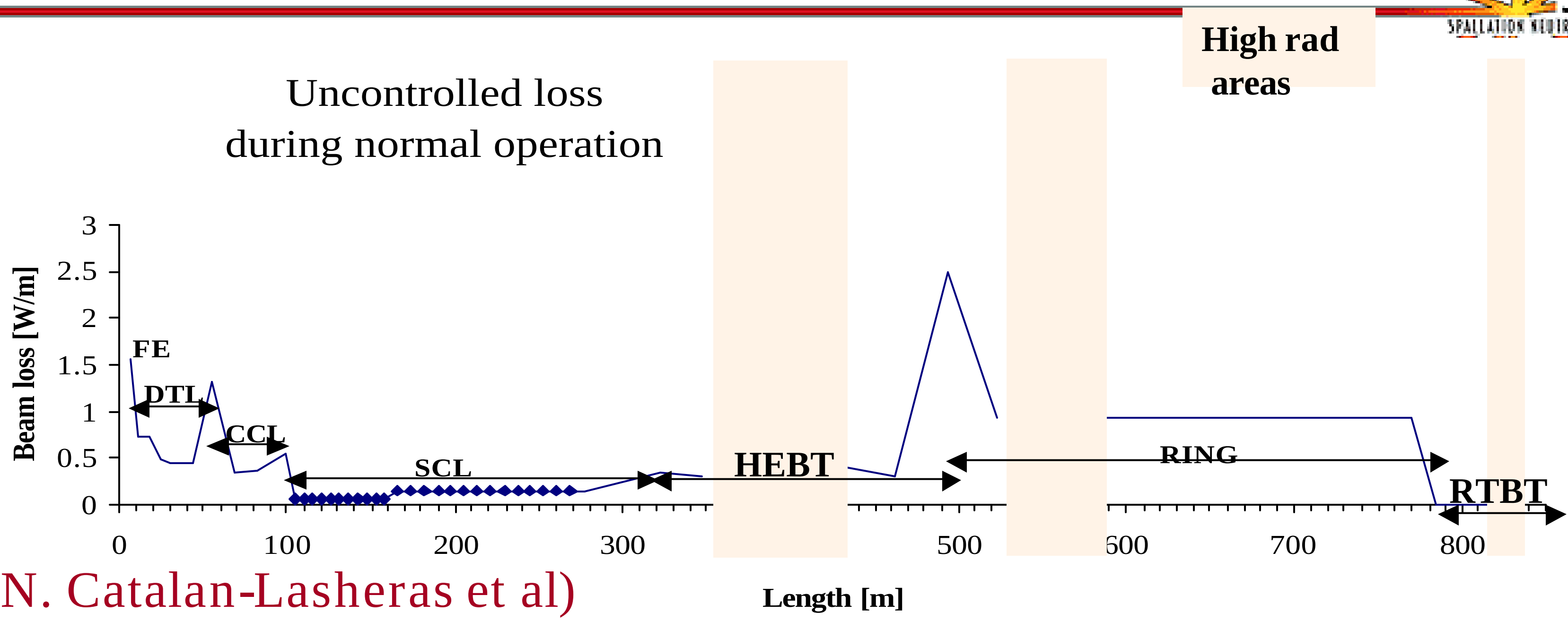
- Minimize uncontrolled beam loss for hands-on maintenance
  - 1 Watt / meter loss of beam power
  - 1 mSv / hour (100 mrem / hour) activation level
  - 10^{-6} / meter fractional beam loss at 1 MW beam power
- Localize beam loss to controlled region
  - Allocate strategic regions to "sacrifice"
  - Apply special practice (remote handling, quick-disconnect vacuum, remote water fitting, …)

Spallation Neutron Source

- Designed for 1.4 MW operation
- 1 GeV proton accumulation in ring
- 1 W / m loss in linac; 10^{-3} loss in ring; >90% cleaning efficiency



Predicted SNS loss distribution



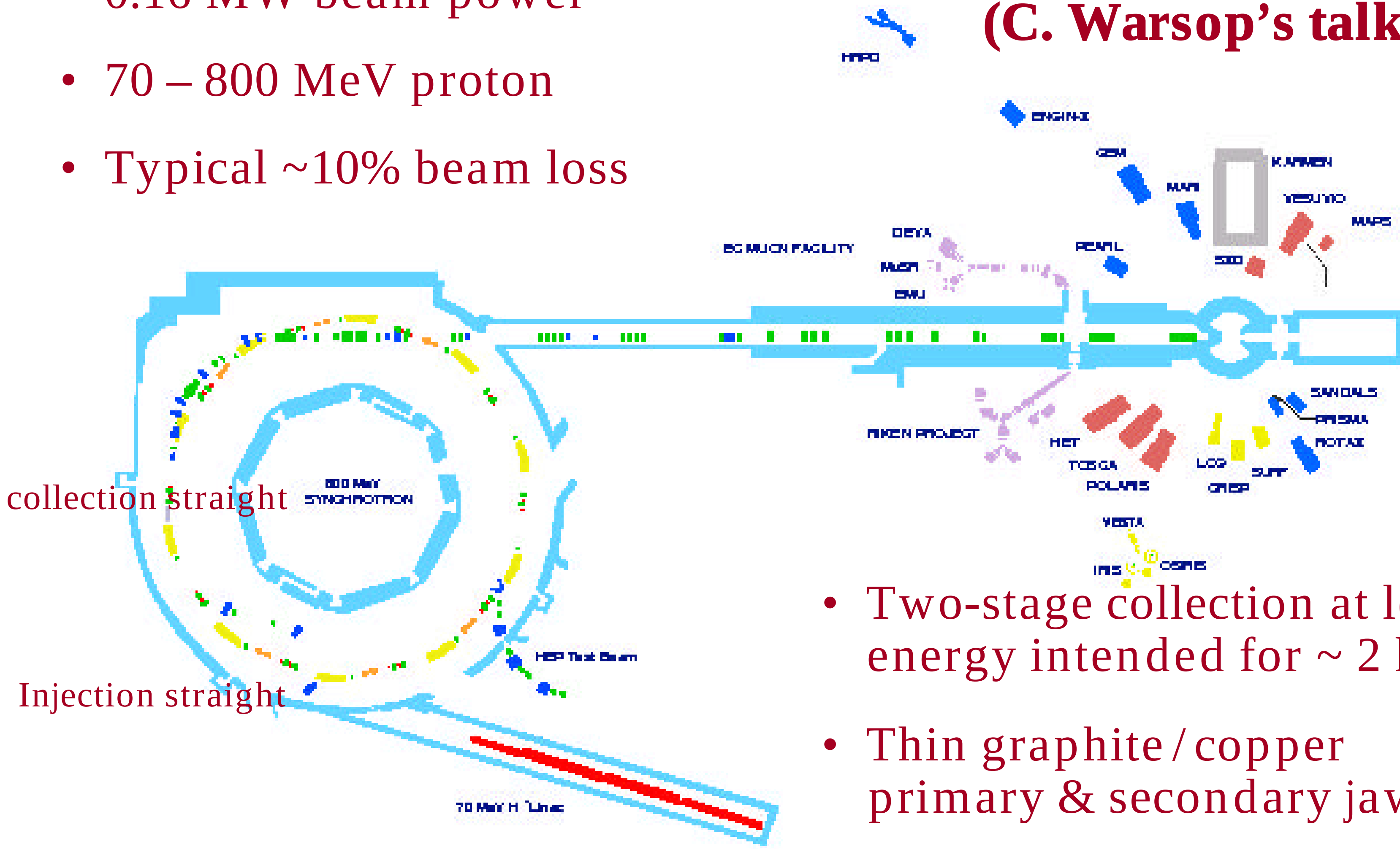
(N. Catalan-Lasheras et al)

Mechanism	Location	Fraction	Power [W/m]
Ring beam halo	collimator	1.9×10^{-3}	2,000
Excited H^0 at foil	collimator	1.3×10^{-5}	20
Energy straggling at foil	collimator	3×10^{-6}	4.5
H- magnetic stripping	injection dipole	1.3×10^{-7}	0.3
Nuclear scattering at foil	injection foil	3.7×10^{-5}	2.5
Collimator inefficiency	all ring	10^{-4}	0.9

ISIS at Rutherford Appleton Lab

- 0.16 MW beam power
- 70 – 800 MeV proton
- Typical ~10% beam loss

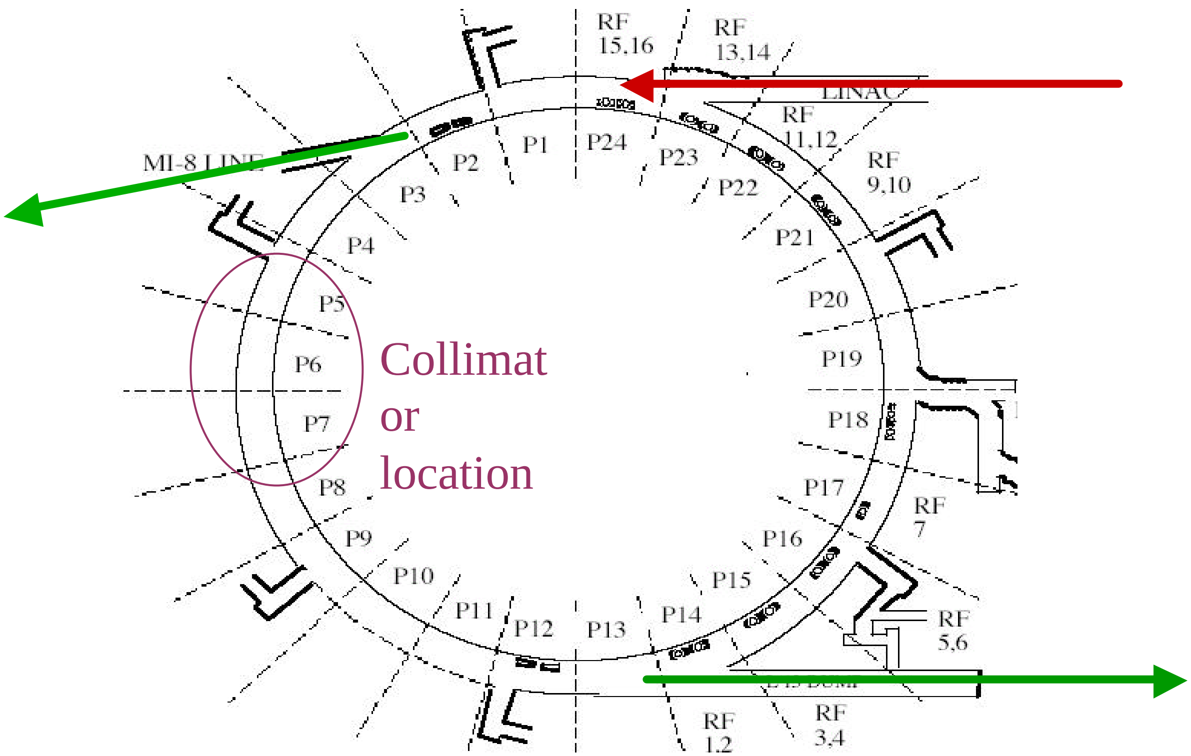
(C. Warsop's talk)



- Two-stage collection at low energy intended for ~ 2 kW
- Thin graphite / copper primary & secondary jaws
- Transverse & momentum

FNAL Booster (E. Prebys, N. Mokhov's talk)

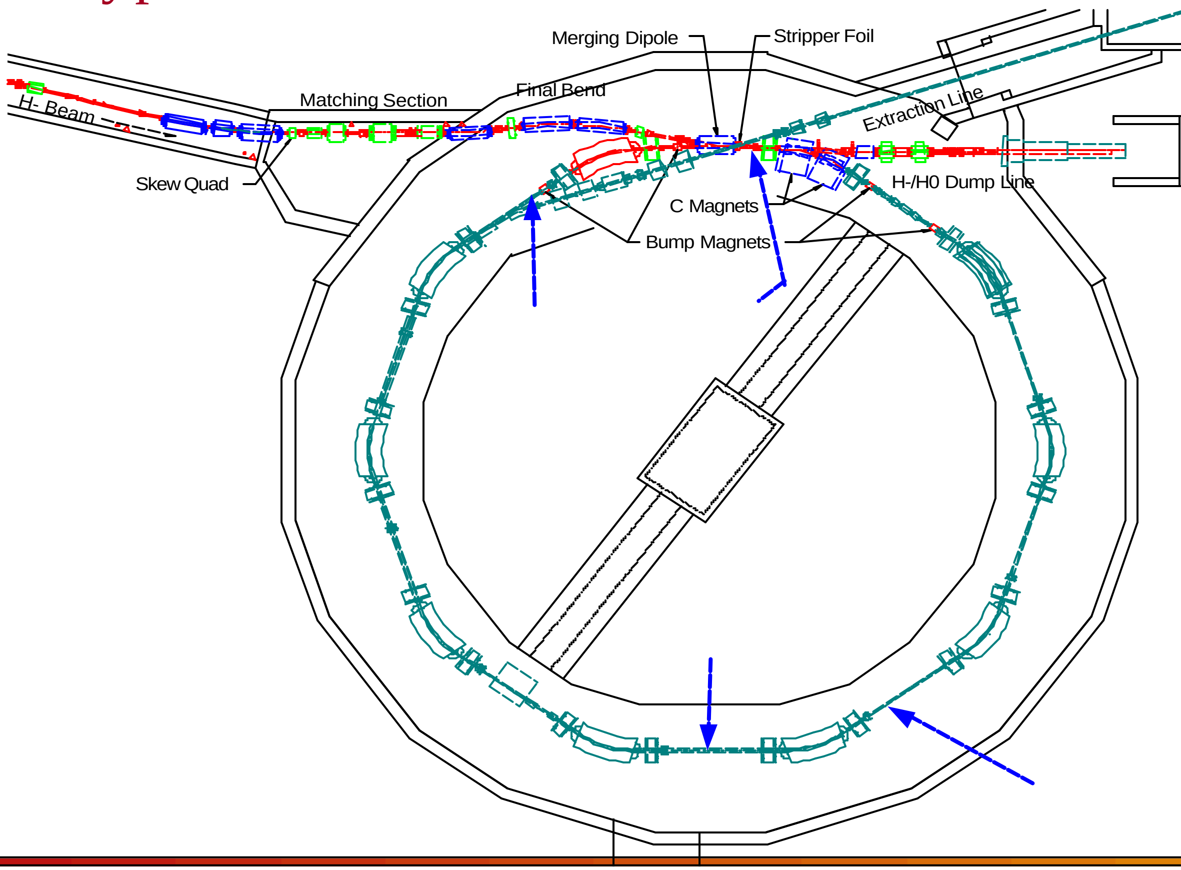
- ~ 0.1 MW beam power
- 0.4 – 8 GeV proton
- Typical ~20% beam loss



- Prototype two-stage system tried in 2002; issues at shielding, heat-load, and serviceability
- New system designed

PSR at Los Alamos (R. Macek's talk)

- 0.08 MW beam power
- 0.8 GeV proton accumulation
- Typical ~ 0.3% beam loss

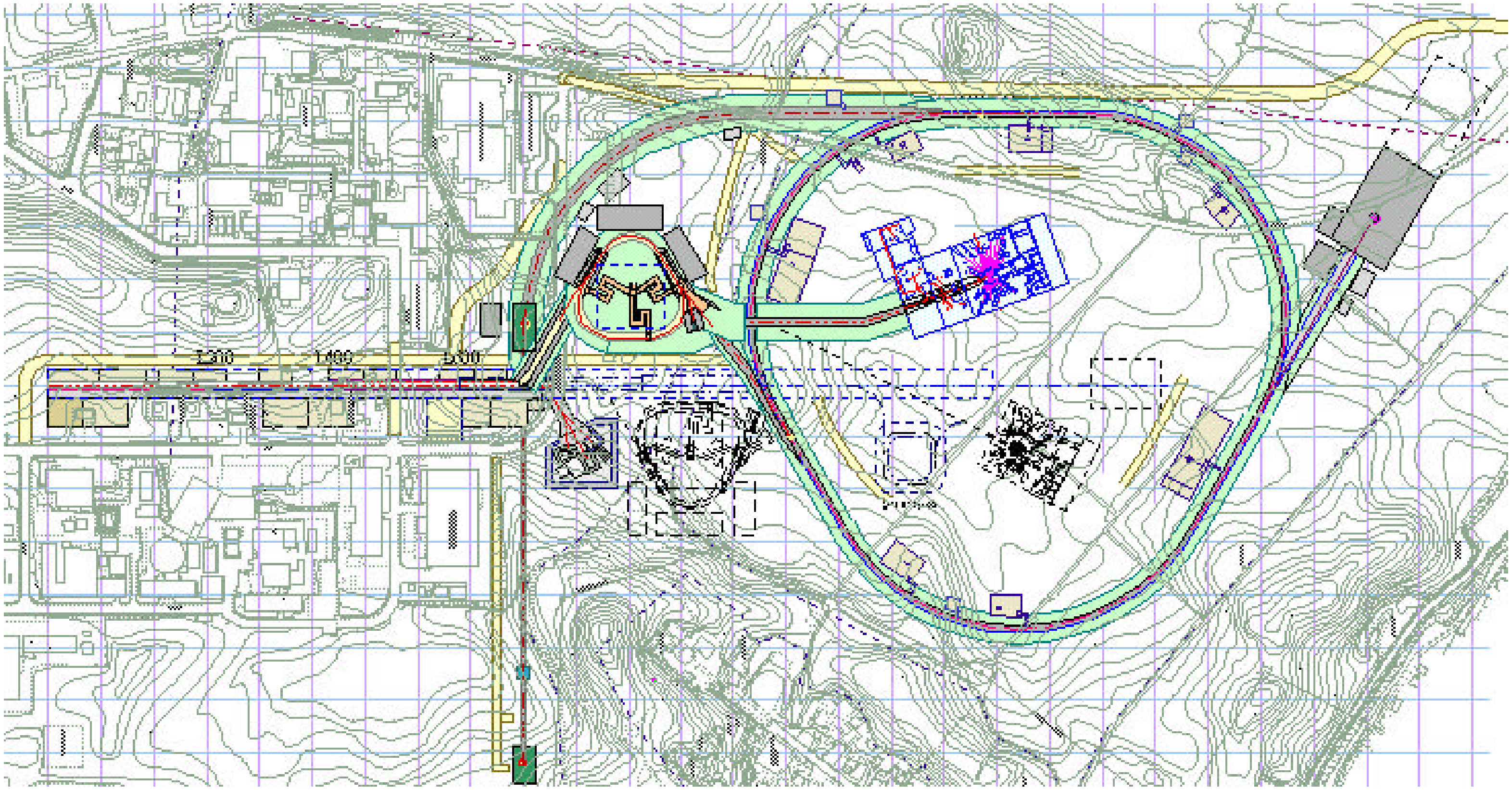


- Single-stage scraping tried & abandoned for enhanced loss due to out-scattering
- Tight beam loss control (new H^- injection, e-p instability control)

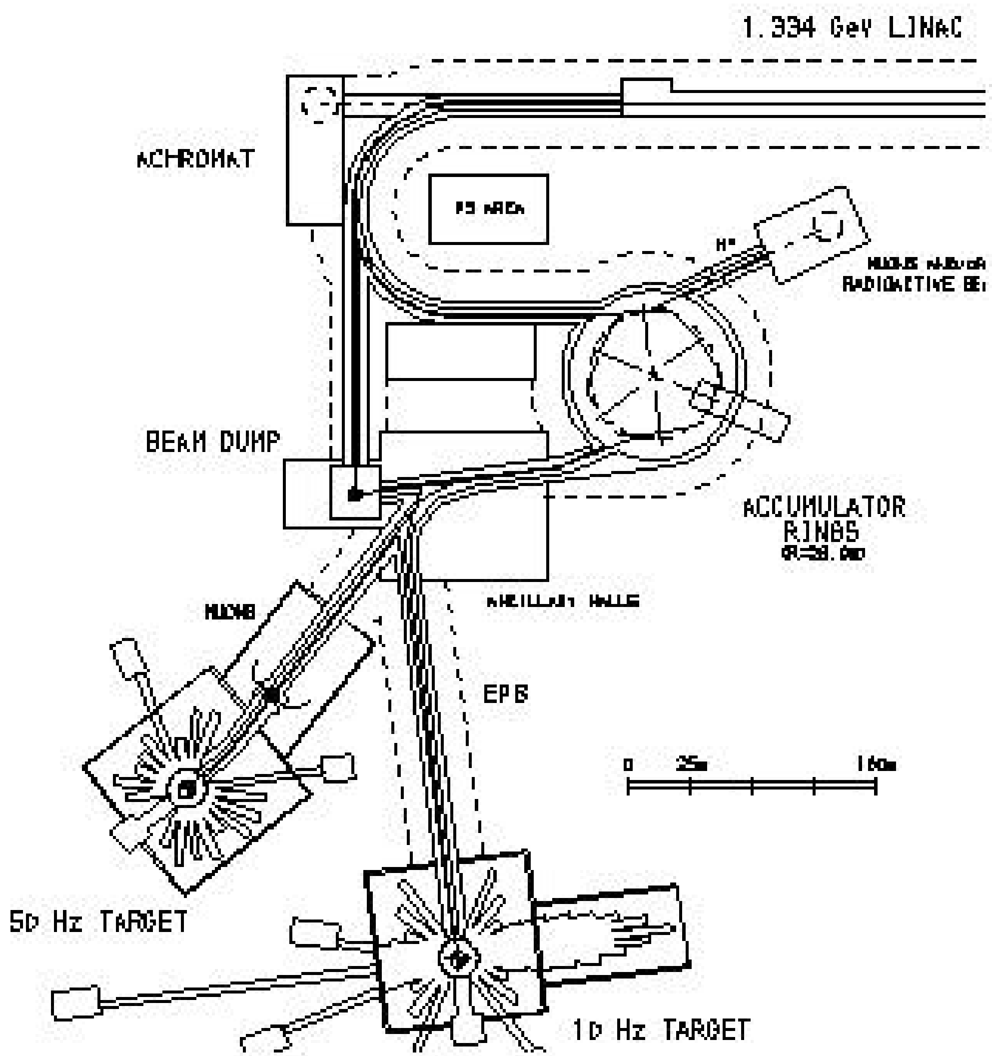
JAERI-KEK's J-PARC (Y. Mori, N. Nakao's talk)

SNS SPALLATION NEUTRON SOURCE

- 1 MW beam power designed
- 0.4 - 3 GeV; 3 – 50 GeV proton
- ~ 1% beam loss tolerated
- Transverse & longitudinal two-stage system designed



European Spallation Source (proposal)



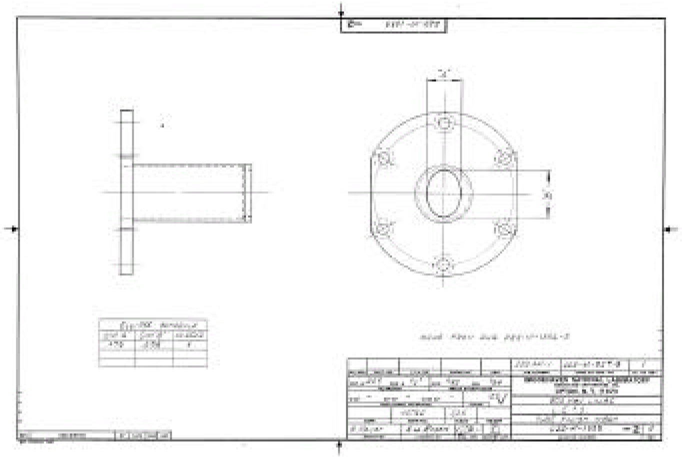
- 5 MW beam power designed
- 1.334 GeV proton accumulation
- Sophisticated multi-stage collimation

Guiding principles

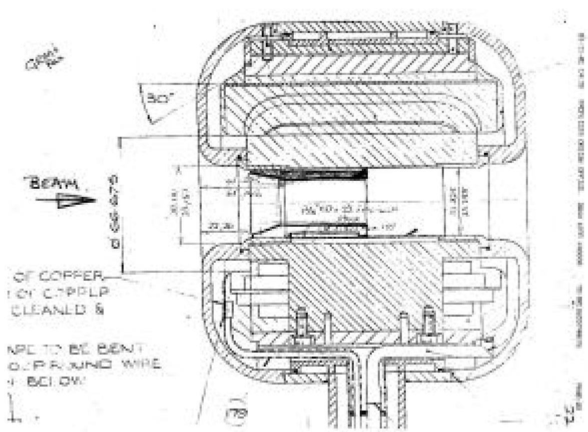
- Minimize sources of beam loss
  - Physical aperture & momentum aperture limitation; space charge; injection loss; magnet errors; instabilities
- Keep major beam loss at low energies
  - Chop beam gap near ion source
  - Collimate beam at low energy (e.g. at drift-tube linac)
- Prepare for both normal and fault conditions
  - Clean beam halo before injection into ring
  - Prepare for ion-source / linac / ring-extraction faults
- Two-stage collimation for increased efficiency
  - Enhance impact parameter, reduce out-scattering
- Impedance, field emission, secondary emission considerations

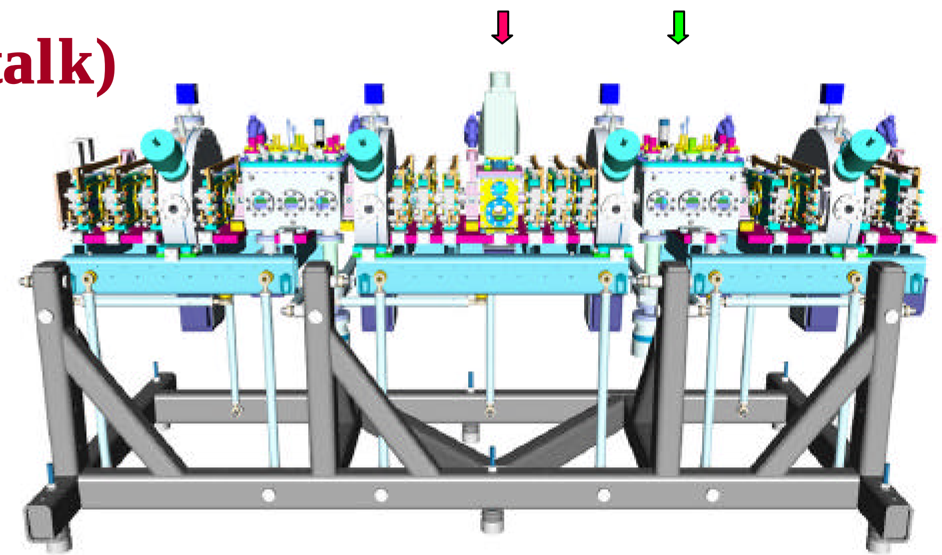
Low-energy cleaning

- BNL linac: Tungsten sleeve in DTL to scrape 5% beam at 750 keV
- ISIS linac: reactor-grade graphite sleeve in DTL tank 2
- SNS:
  - Two-stage chopping in LEBT / MEBT
  - Transverse scraping in MEBT

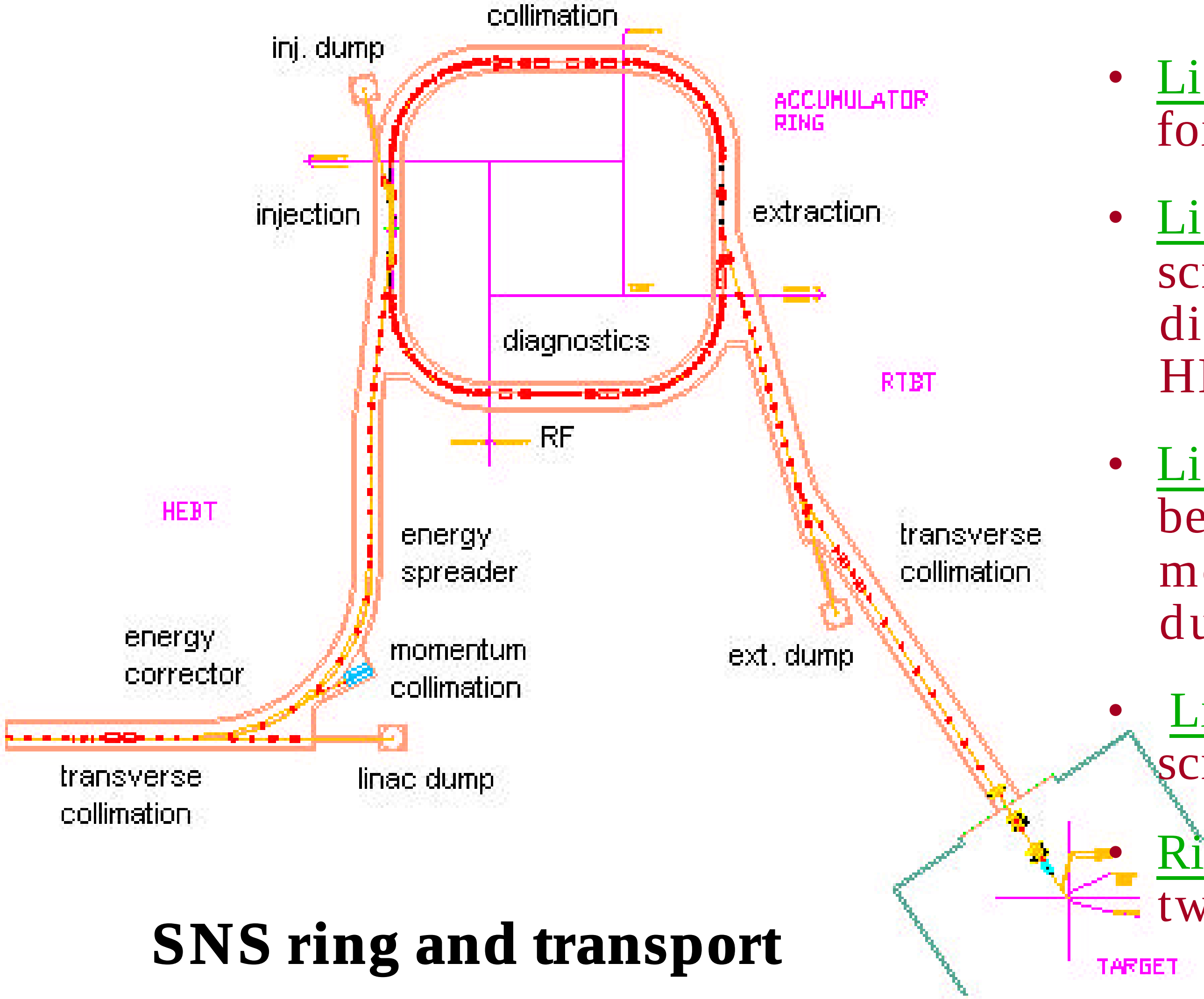


(D. Jeon's talk)





Normal & fault condition protection

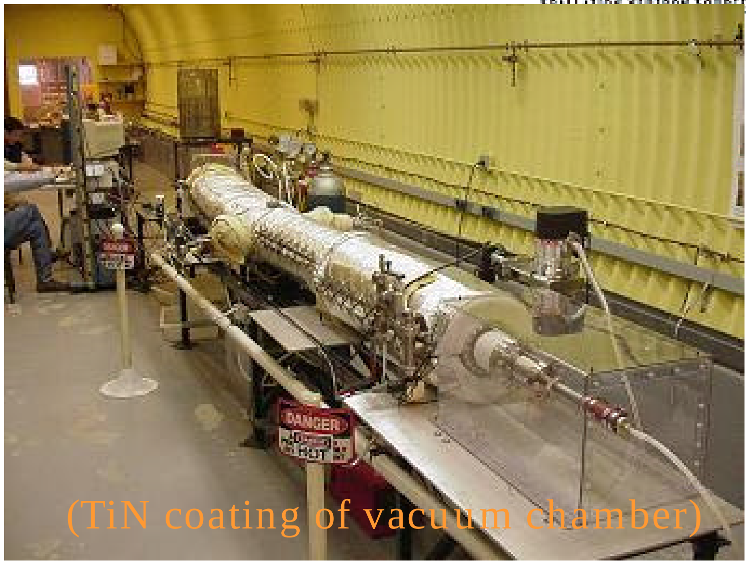


SNS ring and transport

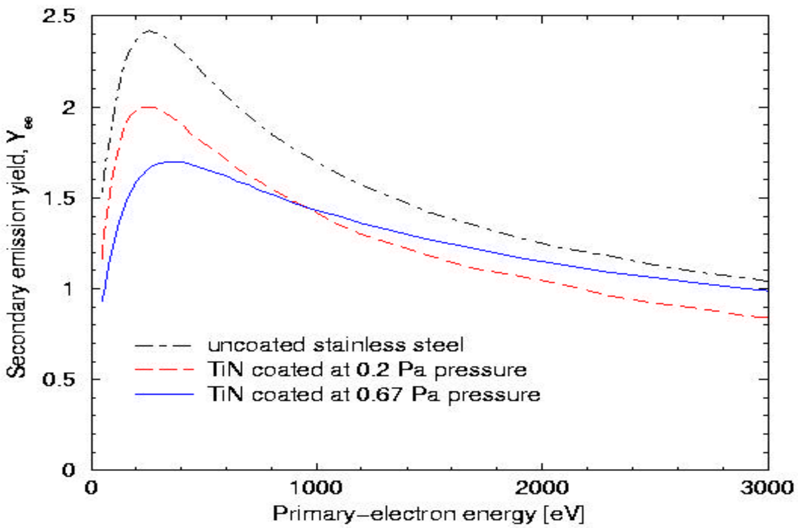
- Linac halo: adjustable foil scraper in HEBT
- Linac energy tail: scraping at high-dispersion location in HEBT
- Linac gap residual: beam-in-gap kicker or momentum collection during initial ramping
- Linac malfunction: scraper in HEBT
- Ring halo: two-stage collimation

Impedance, secondary emission

- Impedance
  – Conducting pass for the image current
  – Tapered steps to avoid resonance structure / sharp field emission
  – Impedance is usually of little concern
    » Large beam size (SNS: ~ 170 m long, ~ 120 mm diameter; no short-bunch wake complication)
    » Large collimator dimension (~ 160 mm diameter; $Z_T \sim 1/b^3$)
- Secondary electron emission
  – Coating to reduce electron multipacting (TiN for SNS ring; NEG?)

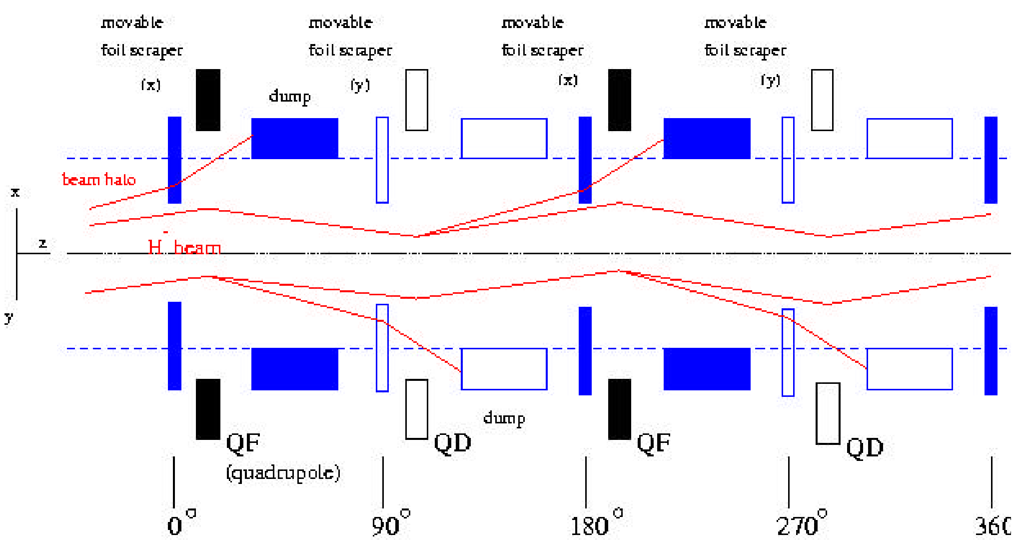


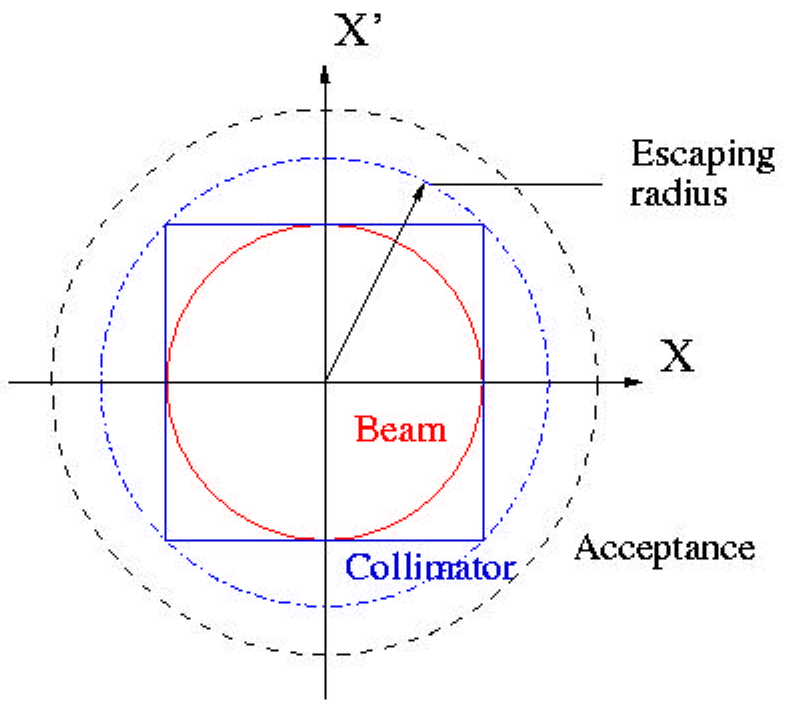
(TiN coating of vacuum chamber)



H$^-$ beam-halo cleaning: transverse

- Use movable striping foil as scraper, deflect the stripped particle with quadrupole for collection
- For single-pass cleaning, require multiple scrapers to enclose different angle of the phase space
- Good lattice candidate: FODO lattice with 90^o phase advance per cell



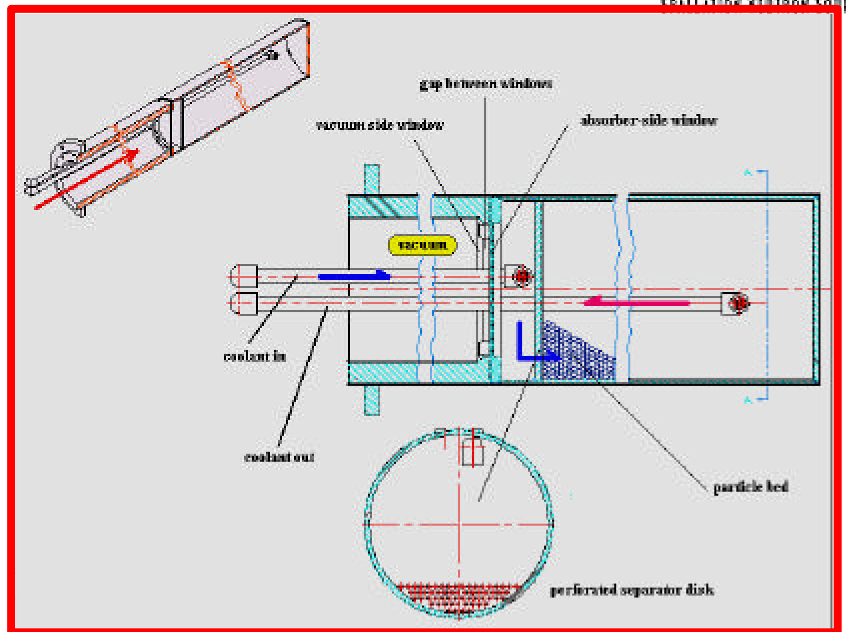


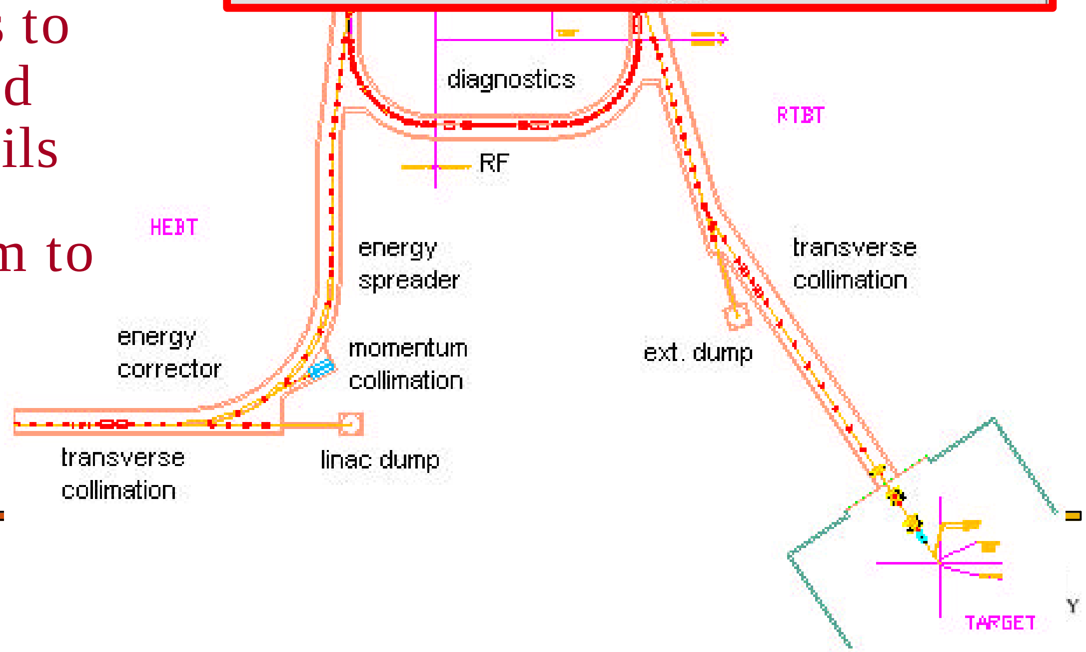
H⁻ beam-halo cleaning: longitudinal

- Collimate at maximum dispersion region

$$D\left|\frac{\Delta p}{p}\right|_{scraping} >> \sqrt{b_x e_{x,99\%}}$$

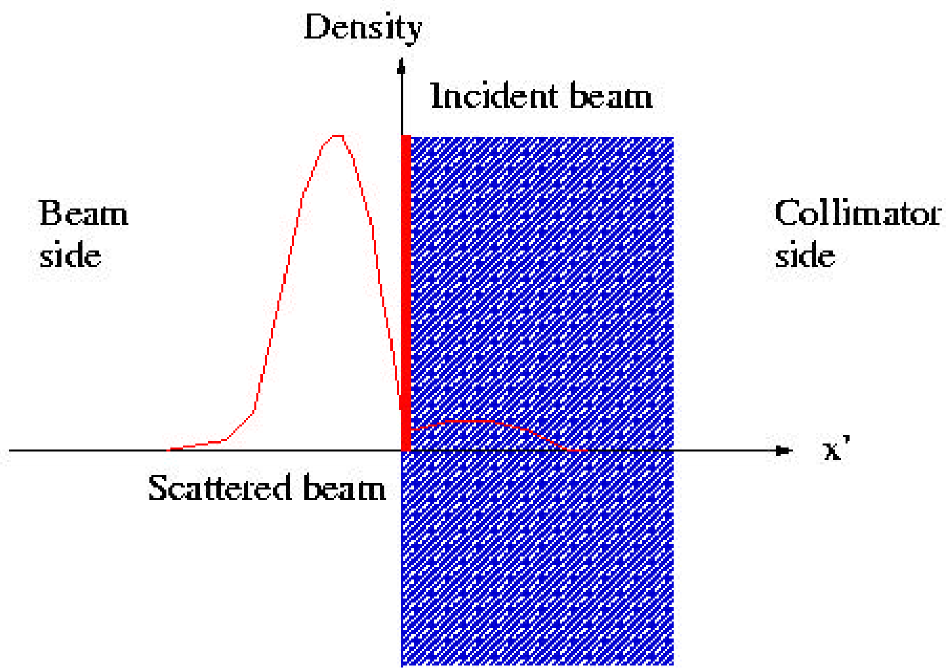
- Bending achromat to create high dispersion within a localized region
- Movable stripping foils to scrape both positive and negative momentum tails
- Guide the scraped beam to the collectors





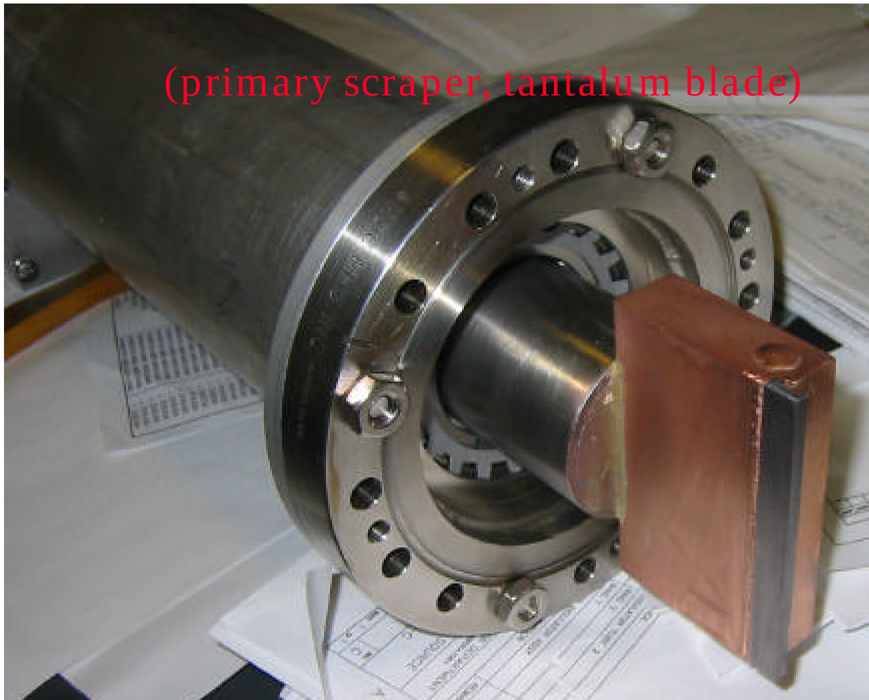
Proton beam-halo cleaning

- Collection efficiency crucially depends on the impact parameter
- To increase overall efficiency, use two-stage system
  - Stage 1: movable scraper. Thin material, length optimized between energy loss and scattering angle
  - Stage 2: collector / collimator. Thick, often fixed, self-shielded & cooled, length chosen to be longer than the stopping distance of the particles



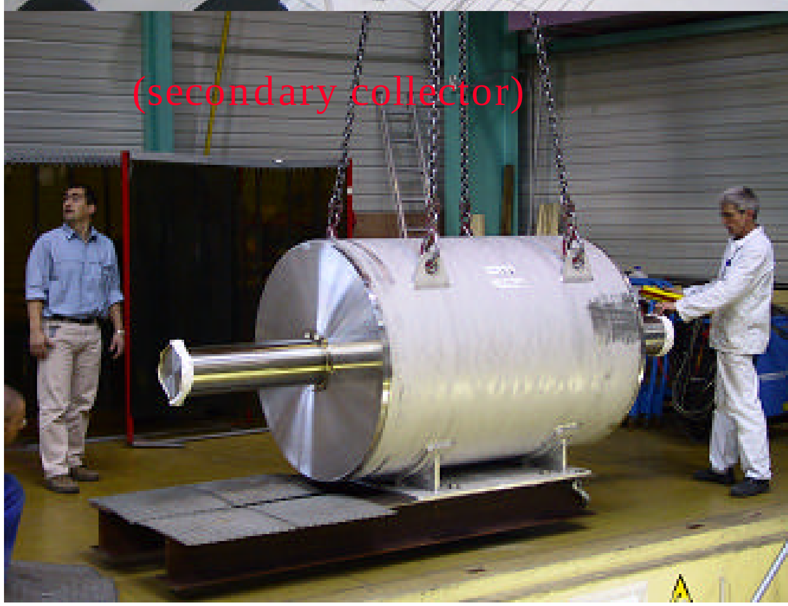
SNS design

(H. Ludewig et al TPAG005; N. Simos WPPE006; N. Catalan-Lasheras, S. Cousineau, et al)

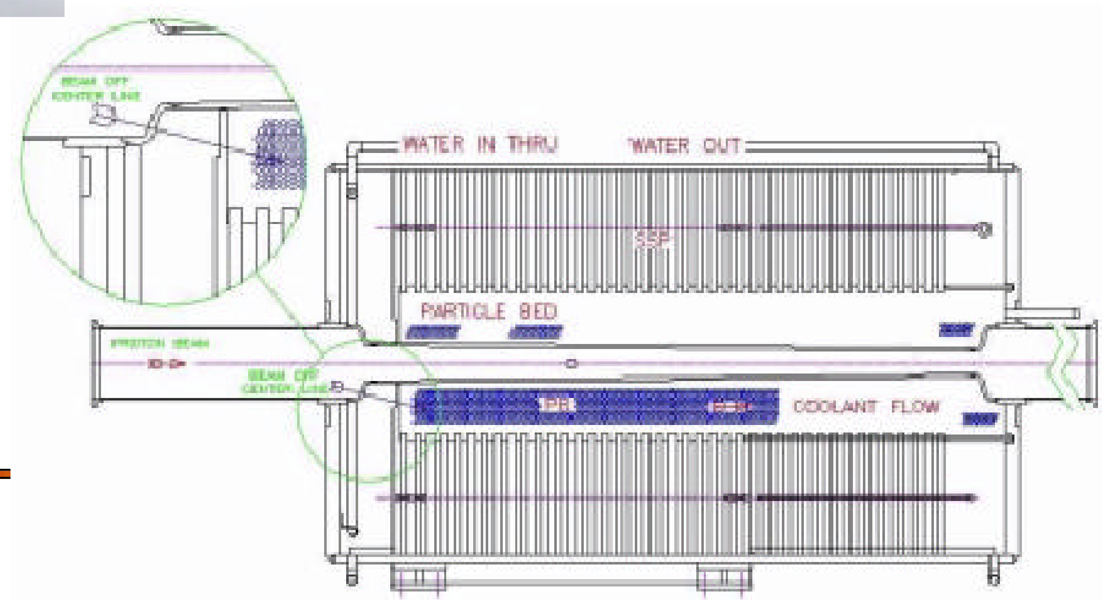


(primary scraper, tantalum blade)

- Two-stage collimation in ring
- Primary scraper (4):
  - Adjustable, thin blades
- Secondary collector (3):
  - Fixed, multi-layer, heavy!
  - Double-wall with He gas for leak detection / protection



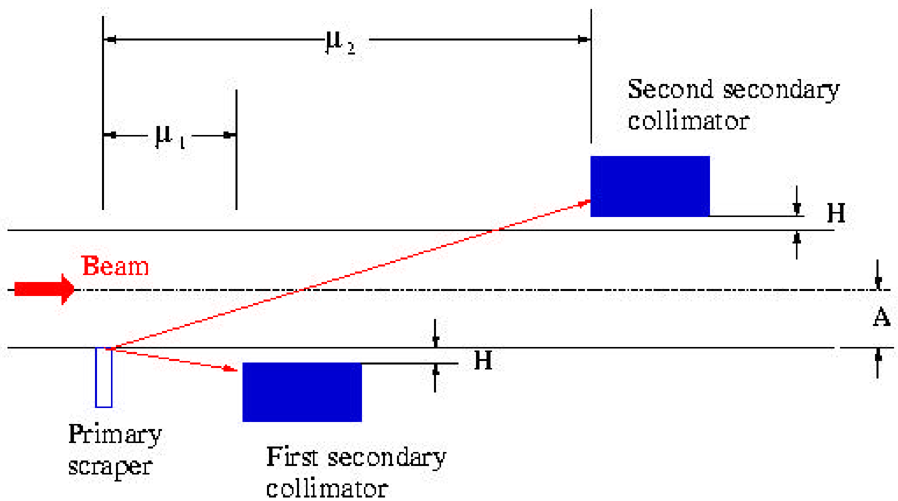
(secondary collector)

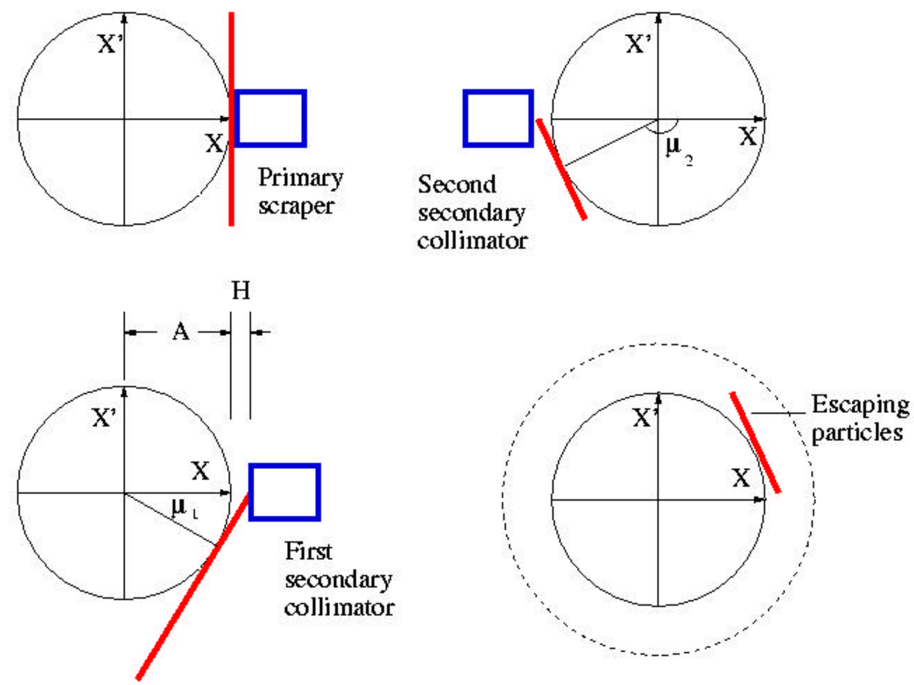


Two-stage collimation optimization

- Comparing with the scraper, the secondary collimator is further away from the primary beam
- Betatron phase advance optimized to minimize escaping
- Detailed simulation is needed considering actual geometry to minimize activation on surrounding magnets

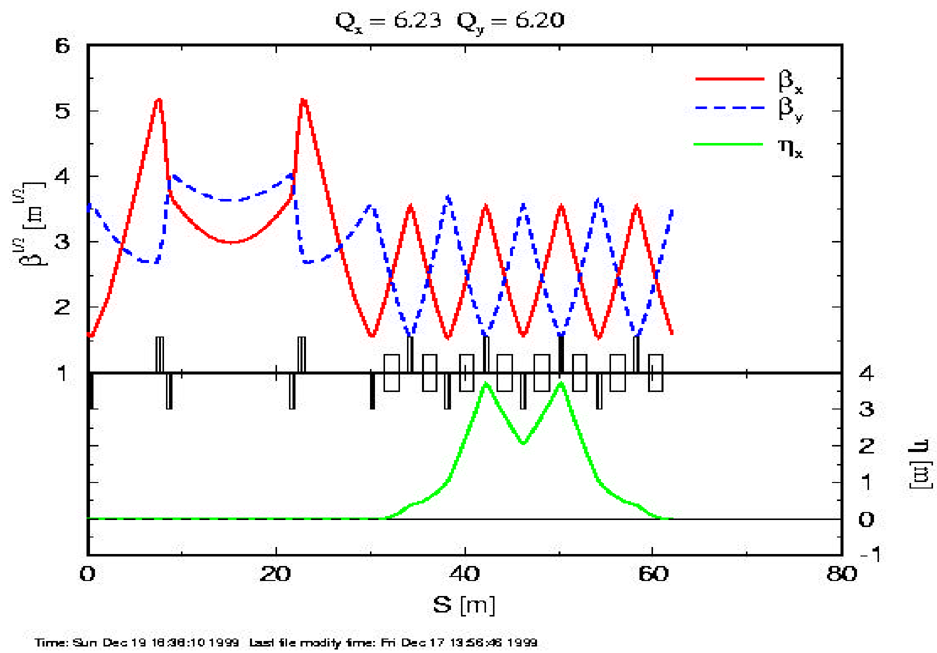
$$m_1 = \cos^{-1}\left(\frac{A}{A+H}\right) \qquad m_2 = p - m_1$$

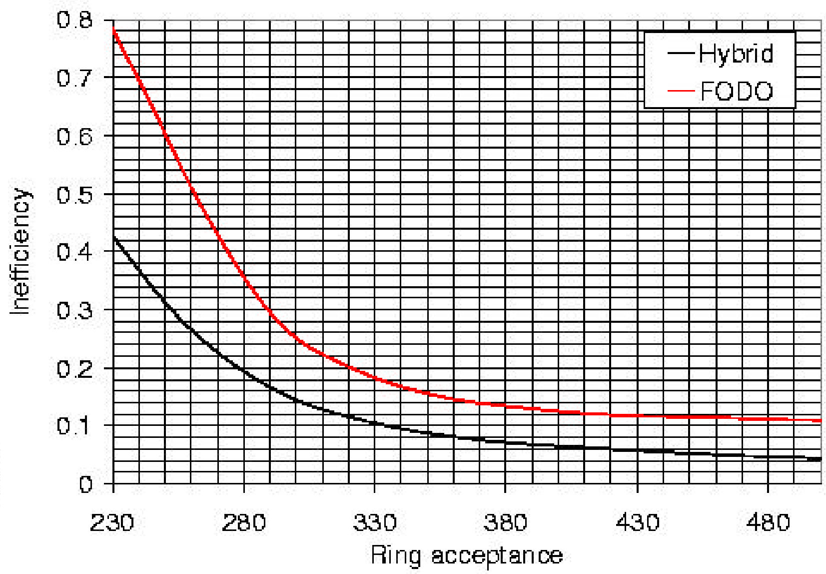




Lattice for transverse collimation

- Dispersion-free region for betatron collimation
- Allow flexible arrangement at optimum phase advance
- H$^-$: e.g. 90 degree phase advance apart to minimize escape
- p: usually prefer doublet / triplet lattice with long drift space

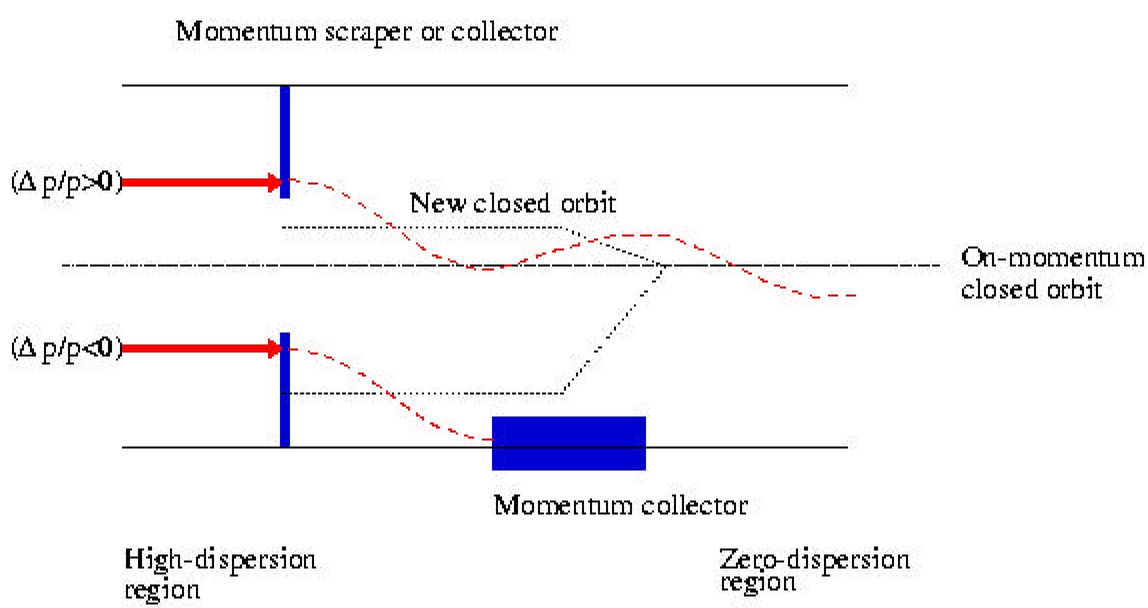




(N. Catalan-Lasheras, et al)

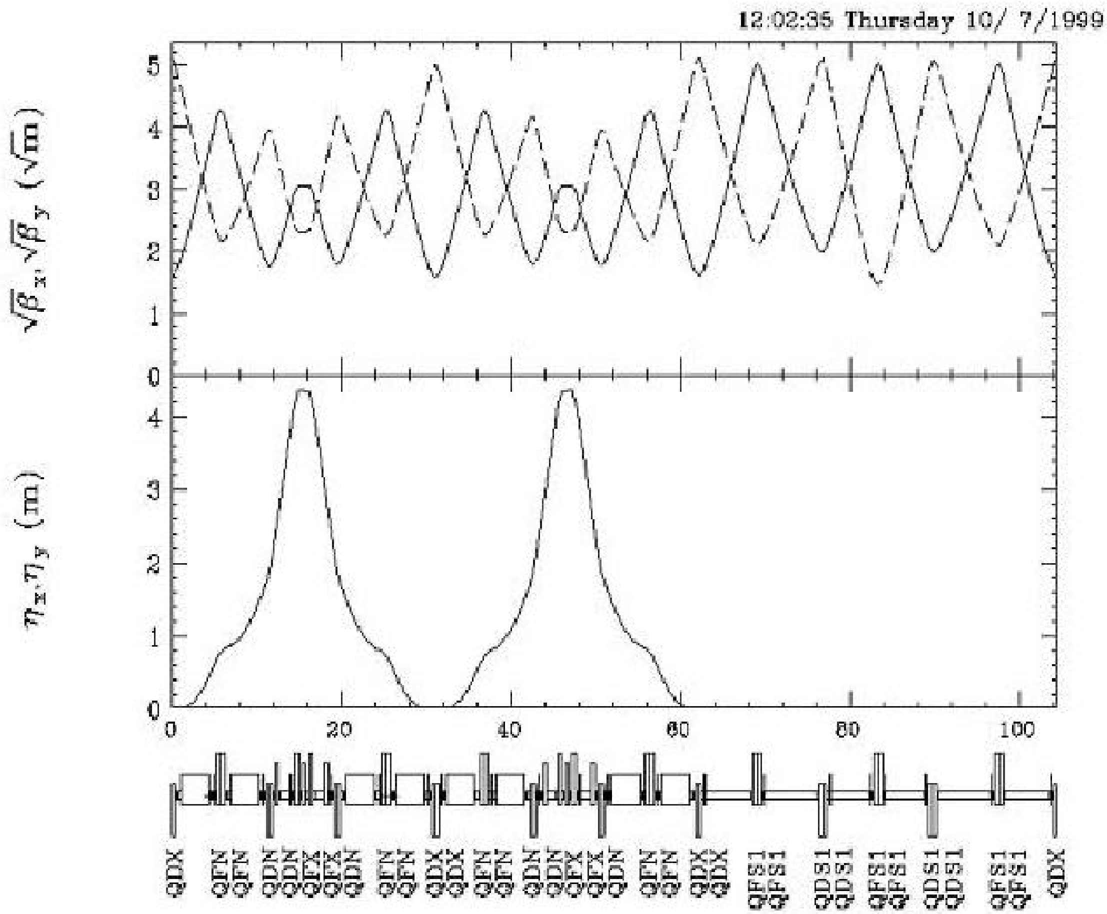
Proton momentum cleaning

- Position scraper at high-dispersion region
- Position collimators preferably also at high-dispersion region
- Positive momentum particle may return to core
- Negative momentum particle needs to be collected
- Compact lattice design is challenging; detailed modeling needed



Lattice for momentum collimation

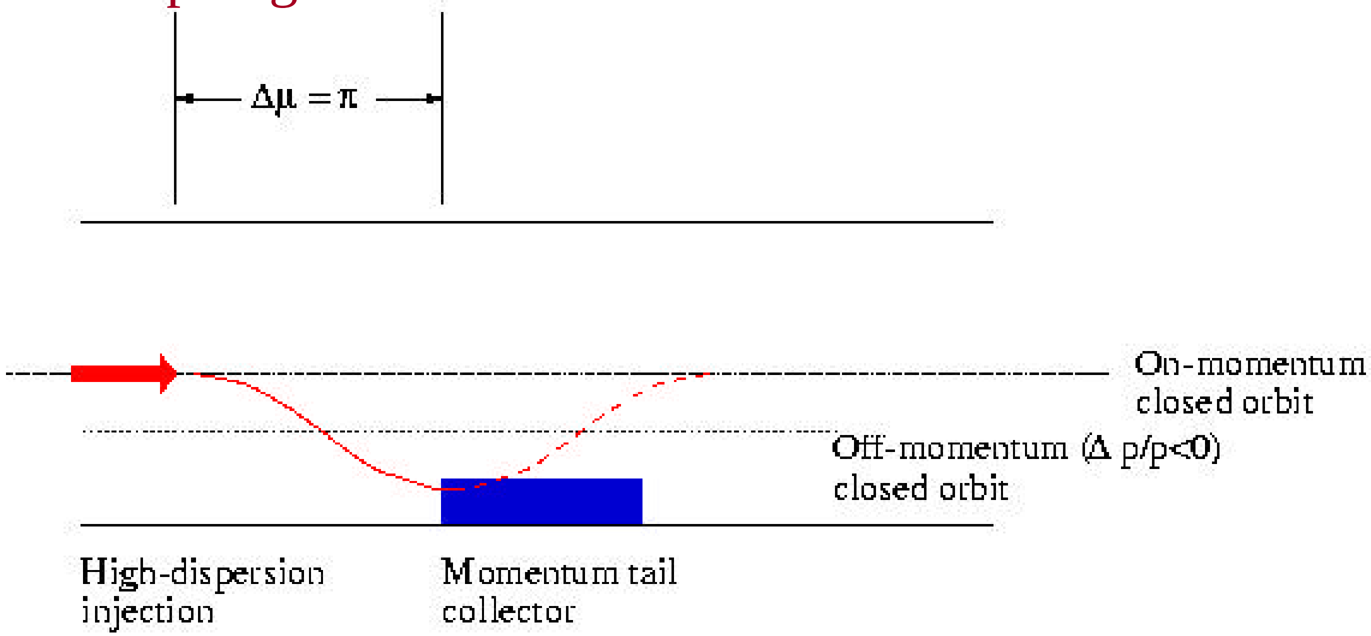
(J-PARC 3 GeV lattice, courtesy S. Machida)



- Split quad for high dispersion (chromatic adjustment & momentum scraping)

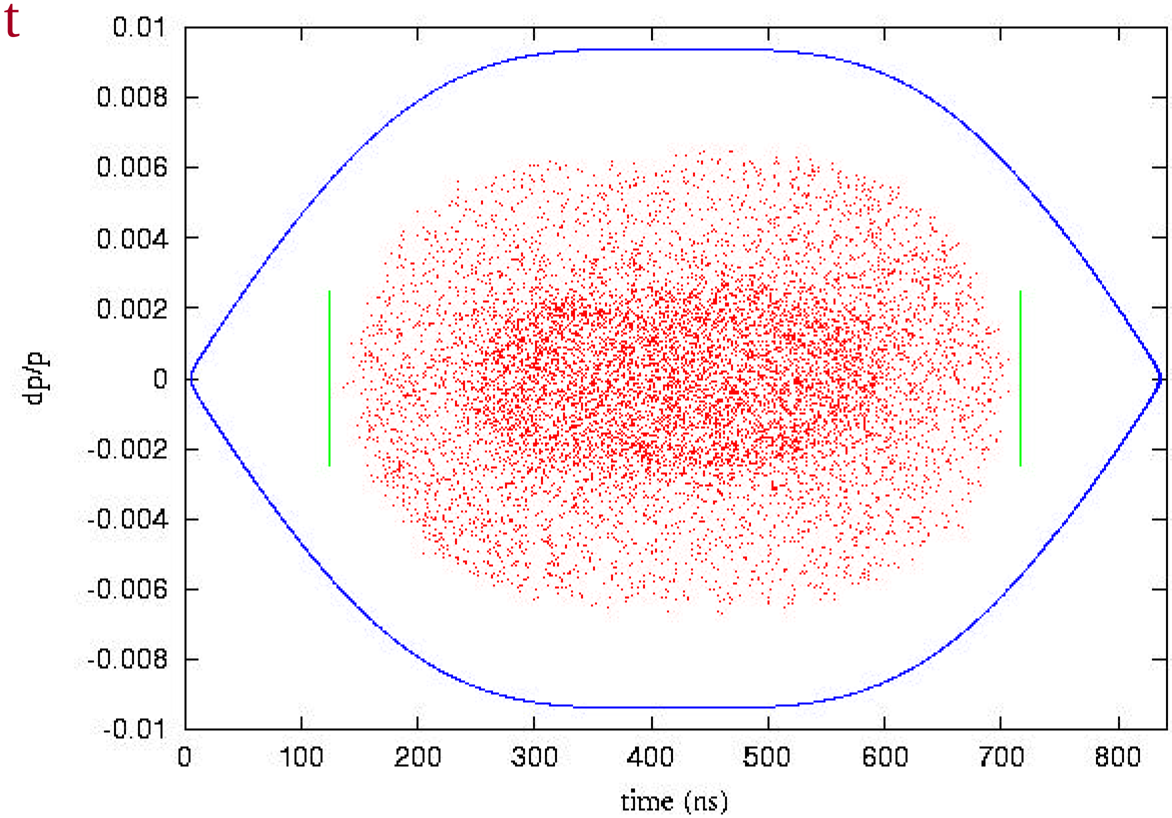
Momentum tail collection

- Initial momentum tail (negative energy)
  - Tails from linac & developed at injection stripping foil
- Inject at high-dispersion region, collect at π horizontal phase-advance downstream (ISIS)
- Not used in SNS and J-PARC – zero-dispersion injection to avoid coupling

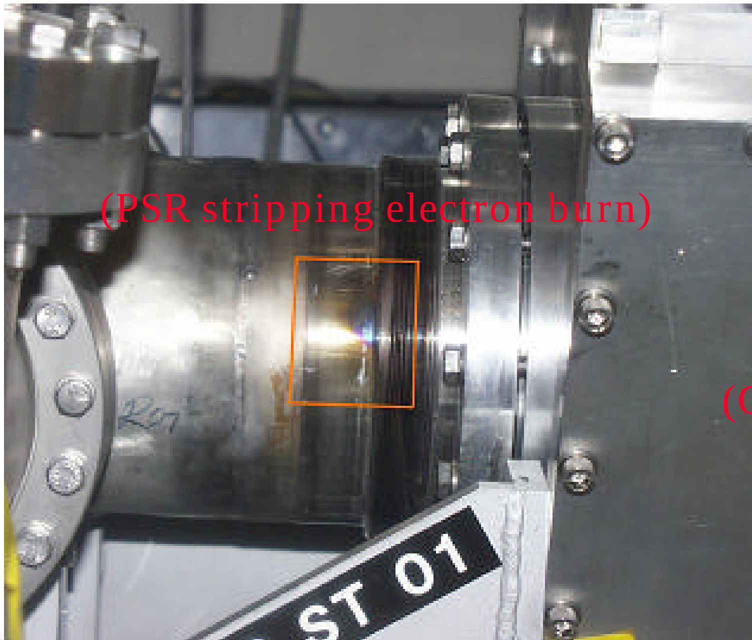


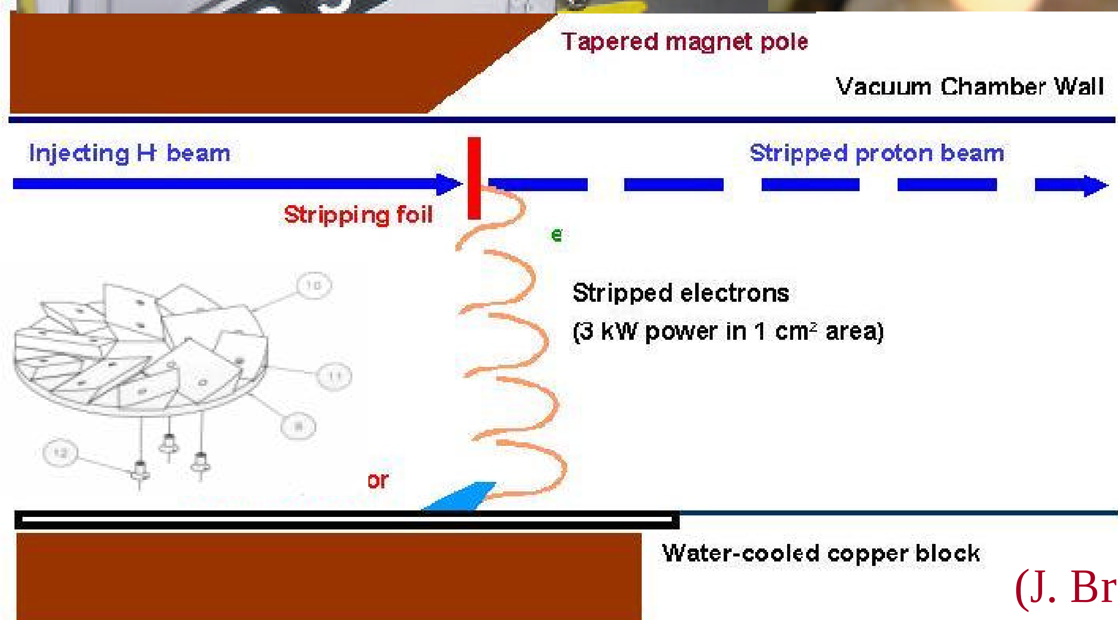
Beam-gap cleaning

- Strip-line kicker resonant at betatron frequency to kick-out particles in tens of turns
- Gated at beam gap, with rise / fall time much shorter that gap length
- Can be used for momentum cleaning since aperture is adequate
- Rise / fall time ~ 30 ns



Injection electron collection





- 2 kW of stripped electrons must be properly collected
- Carbon-Carbon block on water-cooled Cu plate; reduced backscattering
- Window / video monitor
- Tapered magnet ends
- Dedicated clearing electrode (10 kV)

(J. Brodowski, C. J. Liaw, W. Meng, D. Abell, Y.Y. Lee)

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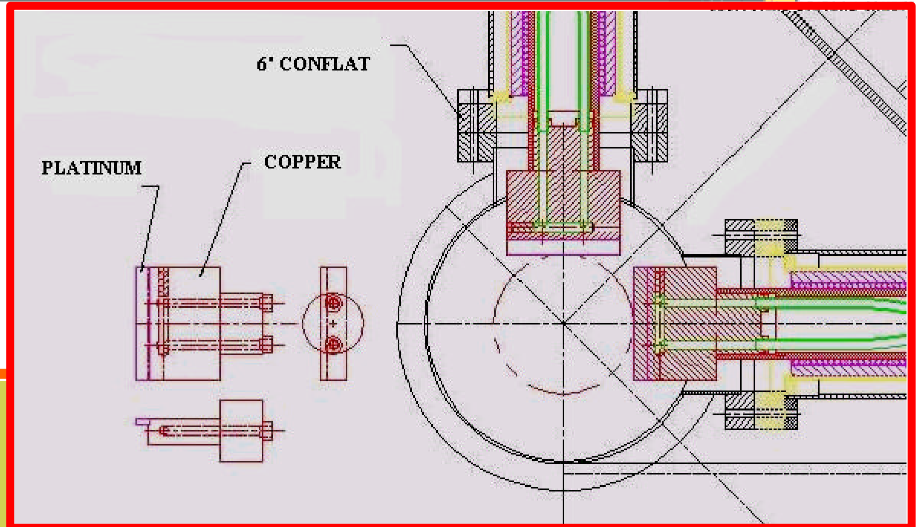
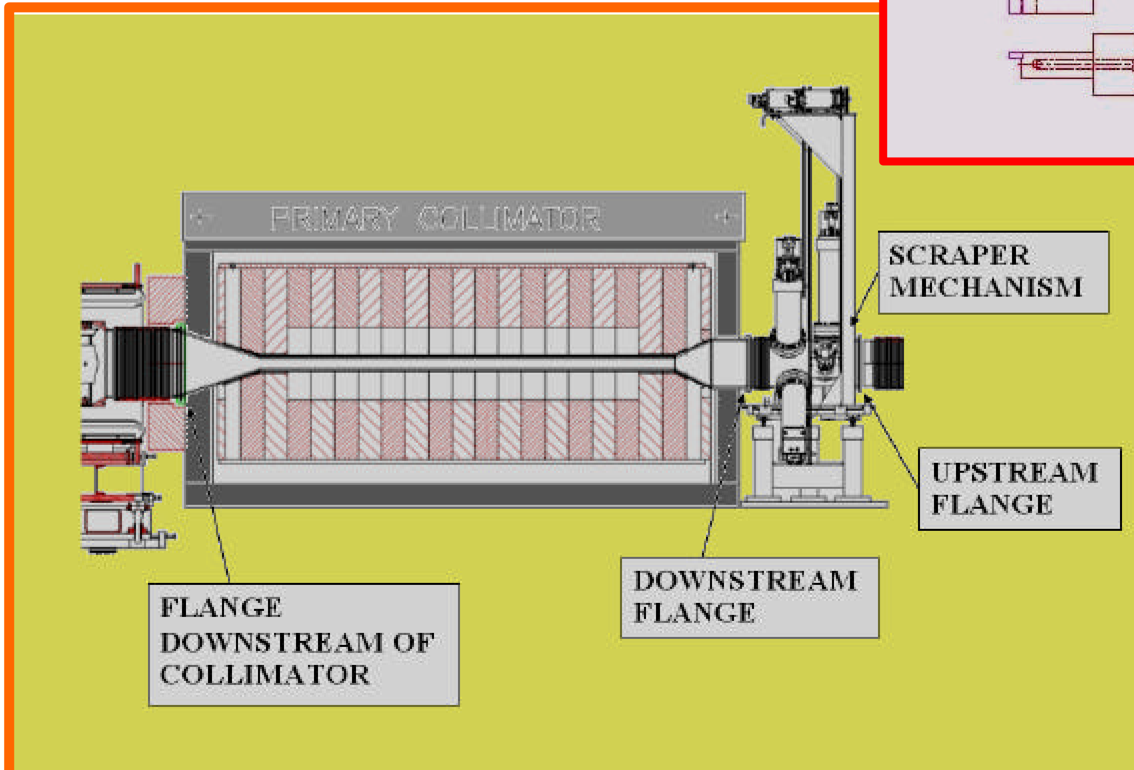
Primary scraper design (SNS)

- Four thin tantalum blades
- Adjustable, each 45º apart, accommodates various beam shape (round / square)

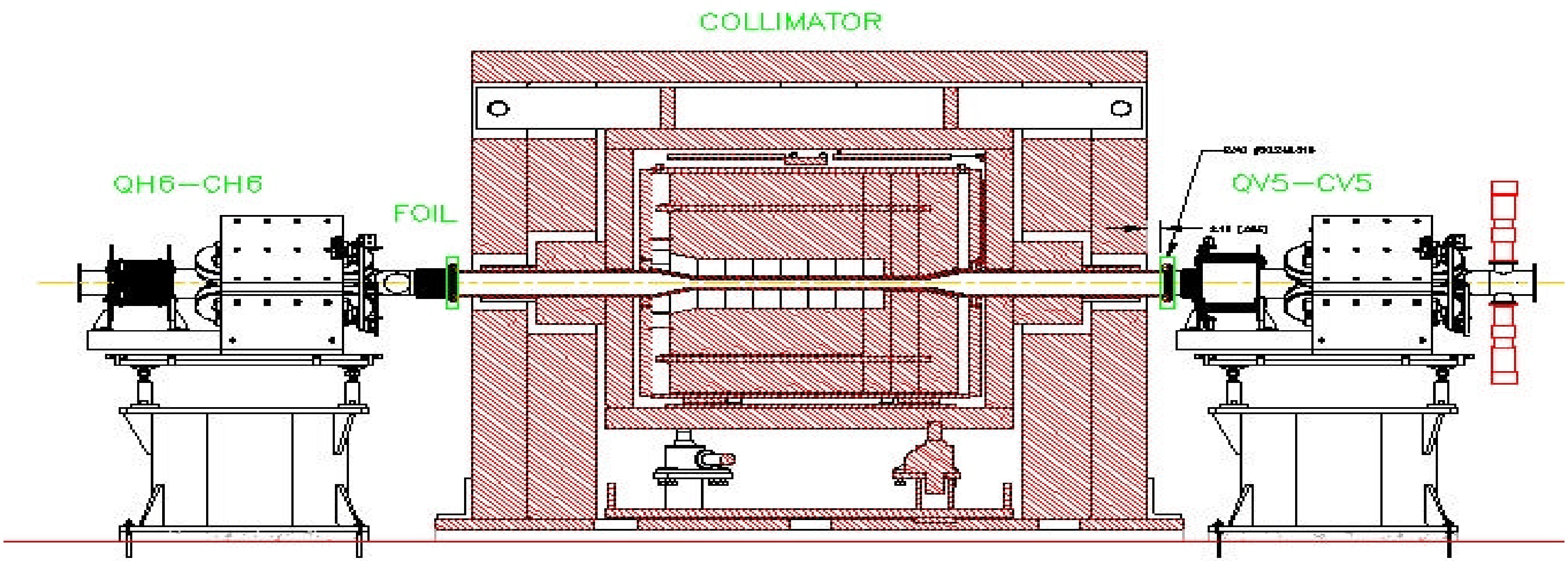




- Shielded to minimize secondary beam & to protect downstream magnets

Secondary collector design (SNS)

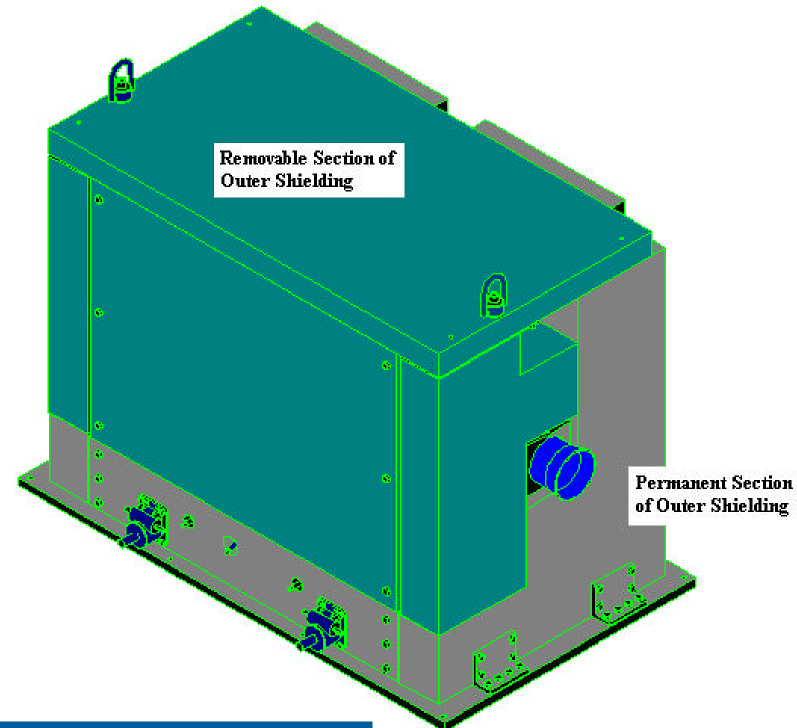
- Length enough to stop primary protons (~ 1 m for 1 GeV beam)
- Layered structure (stainless steel particle bed in borated water, stainless steel blocks) to shield the secondary (neutron, γ)
- Fixed, enclosing elliptical-shaped wall for operational reliability
- Double-wall Inconel filled with He gas for leak detection

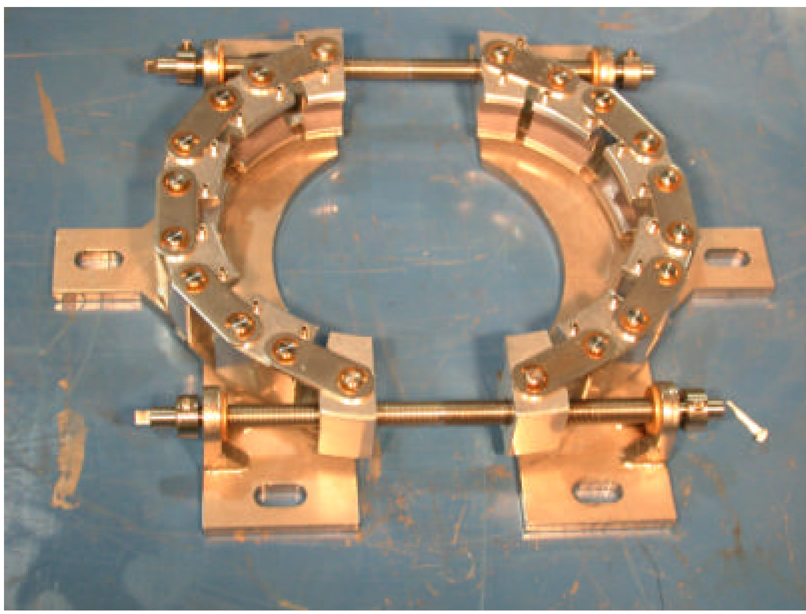


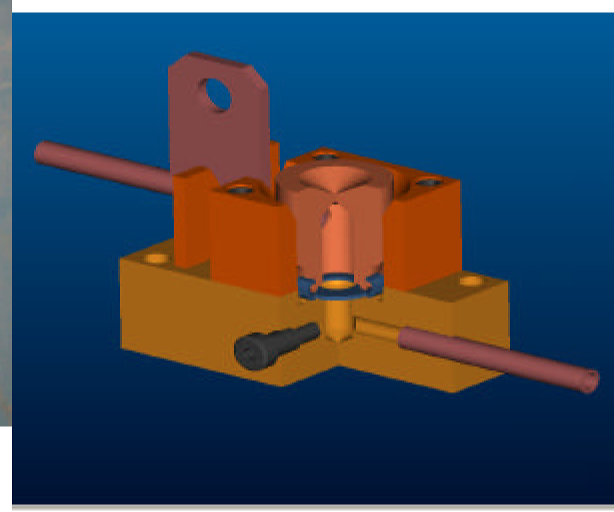
(H. Ludewig, N. Simos, N. Catalan-Lasheras et al)

Maintenance & handling (G. Murdoch's talk)

- All-around crane (25 tons) able to (just) lift collimator
- Remote handling in high-activation area (quick-disconnect vacuum, remote water fitting







Summary

- In high-power proton machines, beam cleaning and collimation are key to localizing beam loss for overall maintainability
- Despite extensive physical and engineering analysis, beam tests are needed to validate the actual design in latest designed systems
- Common issues are shared by high energy, high intensity, and linear collider machines -- A close collaboration is truly valuable.

Acknowledgements

- The SNS team, our collaborators and friends
- J.B. Jeanneret, D. Kaltchev, R. Macek, S. Machida, C. Prior, G. Rees, H. Schonauer, C.M. Warsop ……
- J. Brodowski, P. Cameron, N. Catalan-Lasheras, S. Cousineau, D. Davino, J. Holmes, H. Hseuh, J. Jackson, H. Ludewig, D. Raparia, N. Simos, J. Tuozzolo, R. Witkover ……